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Article

The Effectiveness of *Asystasia gangetica* (L.) T. Anderson Leaf Extract as a Corrosion Inhibitor for Mild Steel in Hydrochloric Acid Medium

Karina Ventika Sari[1], Emriadi[1*], Yeni Stiadi[1]

[1]Department of Chemistry, Faculty of Mathematics and Natural Sciences, Andalas University, Padang, Indonesia

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Abstract. The leaf extract of *Asystasia gangetica* (L.) T. Anderson (EDAG) was successfully obtained via solvent extraction using methanol and was used as a corrosion inhibitor for mild steel. The inhibition effectiveness of the extract in hydrochloric acid solution was analyzed using the weight loss method at 30 °C for 7 hours to determine the corrosion rate and inhibition efficiency. The active compounds were identified through phytochemical tests, while the adsorption type was determined based on thermodynamic parameters. Characterization of surface changes on mild steel was carried out using UV-Vis spectroscopy and Field Emission Scanning Electron Microscopy (FESEM). The results revealed the presence of flavonoids, alkaloids, steroids, triterpenoids, and phenolics, which contribute to the adsorption process on the mild steel surface. The lowest corrosion rate was obtained at a concentration of 8 g/L, namely 0.43 $mg/cm^2.h$, with the highest inhibition efficiency of 73.42%. The R^2 value approaching 1 follows the Langmuir adsorption isotherm, with a ΔG_{ads} value of -23.79, indicating that EDAG molecules are adsorbed on the mild steel surface through mixed adsorption. Surface morphology analysis showed a smoother steel surface after immersion in the inhibitor solution, indicating the formation of a protective layer. Thus, compared to previous studies, EDAG exhibits higher inhibition efficiency and demonstrates potential as an environmentally friendly corrosion inhibitor alternative.

Corresponding Author :
Emriadi
Department of Chemistry, Faculty of Mathematics and Natural Sciences,
Andalas University, Padang, Indonesia
Email : emriadi@sci.unand.ac.id

1. Introduction

Mild steel is a type of low-carbon steel containing approximately 0.05 - 0.25% carbon, making it softer and more easily formed than high-carbon steels. In industry, mild steel is widely used as a construction material for pipes, storage tanks, and process equipment due to its good mechanical properties and relatively low cost. However, in industrial processes that involve acidic solutions such as pickling, acid cleaning, and operations in the oil and gas sector, mild steel is highly susceptible to corrosion [1].

Corrosion is a process of metal degradation or damage caused by chemical or electrochemical reactions between the metal and its environment. This degradation process leads to changes in the metal's properties, such as reduced mechanical strength and gradual loss of mass. Corrosion occurs when a metal reacts with oxygen, water, or aggressive ions such as chloride, forming unstable oxide or salt compounds. Corrosion causes a serious problem in various industrial sectors, particularly in oil and gas, transportation, and construction. Its impacts not only result in significant economic losses due to maintenance and component replacement costs, but also threaten human safety and reduce the efficiency of operational systems [2]. According to the 2016 report by the National Association of Corrosion Engineers (NACE International), global corrosion related losses are estimated at approximately USD 2.5 trillion per year, equivalent to about 3.4% of the world's GDP, and the economic impact varies across countries [3].

Various approaches have been developed to slow down the occurrence of corrosion, including providing protection at the anodic and cathodic areas, coating the metal surface, and using inhibitors. Among these methods, the use of corrosion inhibitors is one of the most effective techniques for preventing corrosion, particularly in steel. Economical, environmentally friendly, and easily applicable inhibitors have been widely developed to protect metals from corrosion damage. In general, corrosion inhibitors are solid or liquid substances capable of reducing the aggressiveness of the medium and decreasing the rate of metal dissolution. Based on their chemical nature, inhibitors can be classified into two categories: organic and inorganic inhibitors [4].

Currently, numerous studies focus on utilizing plant extracts as natural sources of corrosion inhibitors as an alternative to synthetic inhibitors, which are often toxic and less environmentally friendly. Chemically, corrosion inhibitors generally contain heteroatoms such as nitrogen (N), oxygen (O), sulfur (S), and phosphorus (P), which possess lone pairs of electrons [5]. These electrons can interact with Fe^{2+} ions through coordination covalent bonding, allowing the inhibitor molecules to adsorb onto the steel surface and form a protective layer. This layer prevents direct contact between the metal and the corrosive medium, thereby effectively reducing the corrosion rate [6].

Asystasia gangetica (L.) T. Anderson, also known as Chinese violet, is a Southeast Asian plant that has become widely distributed across tropical regions of Africa and Asia [7]. The leaf extract of *Asystasia gangetica* (L.) T. Anderson contains secondary metabolites such as flavonoids and phenolics that are rich in hydroxyl (-OH) groups, as well as alkaloids containing nitrogen atoms [8-9]. The lone pairs of electrons in these compounds also act as electron donors, thereby enhancing the adsorption capability of the extract on the steel surface [10]. Several studies have demonstrated the effectiveness of leaf extracts as natural inhibitors. *Gleichenia linearis Burm* leaf extract provided an inhibition efficiency of approximately 52.5% at 30 °C [11]. Another study using *Luffa cylindrica* leaf extract achieved an inhibition efficiency of 69,8% at the same temperature [12], while research utilized *olive* leaf extract reported a maximum efficiency of 53% at the same temperature [13].

Although various natural materials have been widely investigated as corrosion inhibitors, the use of *Asystasia gangetica* (L.) T. Anderson leaf extract has not yet been reported. However, this plant is known to contain secondary metabolites whose functional groups can act as corrosion-retarding agents. This study offers a new approach by utilizing *Asystasia gangetica* (L.) T. Anderson leaf extract as a corrosion inhibitor, which has not been previously explored. Therefore, this research was conducted with the following objectives to determine the effect of *Asystasia gangetica* (L.) T. Anderson leaf extract on the corrosion rate, to identify the type of adsorption isotherm involved in the corrosion inhibition process by *Asystasia gangetica* (L.) T. Anderson extract, to analyze the morphological changes on the steel surface before and after the addition of the extract.

2. Experimental Section

2.1. Materials

The materials used included *Asystasia gangetica* (L.) T. Anderson leaf extract (EDAG), obtained from Pauh, Padang. Which had been dried and ground into powder, as well as mild steel plates measuring 3 cm × 2 cm × 1 mm. Additional chemical reagents included 1 M hydrochloric acid, methanol, acetone, chloroform, distilled water, magnesium powder, acetic anhydride, H_2SO_4, Mayer's reagent, and $FeCl_3$. The instruments used in this study consisted of an oven, rotary evaporator, water bath, analytical balance (Ohaus CP 214), UV-Visible spectrophotometer, Field Emission Scanning Electron Microscopy (FESEM) and a USB digital microscope.

2.2. Extraction of *Asystasia gangetica* (L.) T. Anderson

The EDAG samples were washed, dried, and ground into powder. The leaf powder was repeatedly macerated with methanol to obtain the methanolic extract of EDAG. The extract was then filtered and evaporated using a rotary evaporator to remove the solvent, resulting in a concentrated extract of *Asystasia gangetica* (L.) T. Anderson leaves.

2.3. Phytochemical Screening of *Asystasia gangetica* (L.) T. Anderson Leaf Compounds

The flavonoid test, 2 mL of the EDAG dissolved in methanol was added with magnesium powder and a few drops of hydrochloric acid. The appearance of a reddish color indicates the presence of flavonoid compounds [14]. For the alkaloid test, 2 mL of the methanolic EDAG extract was added with sulfuric acid and shaken, followed by the addition of a few drops of Mayer's reagent. The formation of a precipitate indicates a positive result for the presence of alkaloid compounds [11].
The test for steroids and triterpenoids was performed by placing a few drops of the EDAG extract on a spot plate, followed by the addition of several drops of the Liebermann-Burchard reagent. The appearance of an orange-red color indicates a positive result for triterpenoids, whereas a bluish coloration indicates the presence of steroid compounds. For the saponin test, 2 mL of the EDAG extract was added with hydrochloric acid, then shaken for 5 seconds. The formation of persistent foam indicates a positive result for saponin compounds [15]. For the phenolic test, 2 mL of the EDAG extract was added with a few drops of $FeCl_3$. The appearance of a purple coloration indicates the presence of phenolic compounds [16].

2.4. Weight Loss Measurement

The preparation and testing of steel specimens were carried out with reference to ASTM G31-21, which specifies the weight loss method using immersion in hydrochloric acid solution, as well as the cleaning procedures for specimens before and after testing [17]. The steel specimens, previously cleaned with acetone, were weighed and recorded as the initial mass (m_1), then immersed in 100 mL of 1 M hydrochloric acid solution containing various concentrations of EDAG inhibitor (0, 1, 2, 4, 6, and 8 g/L) at 30 °C for 7 hours. After immersion, the steel specimens were rinsed with distilled water, dried, and reweighed to obtain the final mass (m_2). The experiment was repeated three times to obtain average values and the corrosion rate was calculated from the weight loss Δm using the following equation:

$$V_{corr} = \frac{\Delta m}{A \times t}$$

Where V_{corr} is the corrosion rate ($mg/cm^2.h$), A is the surface area (cm^2), and t is the immersion time (hours) [18]. From the corrosion rate, the inhibition efficiency (IE%) can be determined using the following equation:

$$IE\ (\%) = \frac{V_{corr\ (blank)} - V_{corr\ (inh)}}{V_{corr\ (blank)}} \times 100\%$$

Where $V_{corr\ (blank)}$ is the corrosion rate of the blank solution ($mg/cm^2.h$), and $V_{corr\ (inh)}$ is the corrosion rate in the presence of the inhibitor ($mg/cm^2.h$).

2.5. UV-Vis Analysis

UV-Vis characterization was performed to analyze the adsorption capability related to the corrosion inhibition mechanism involving donor acceptor interactions between the vacant orbitals on the steel surface and the lone electron pairs of the active compounds present in the EDAG extract. UV-Vis measurements were conducted using a spectrophotometer within a wavelength range of 200-800 nm, with 1 M hydrochloric acid serving as the blank [19]. The sample solution was prepared from the EDAG extract obtained after immersion with mild steel for 7 days at an optimum inhibitor concentration of 8 g/L. Additional analyses were also carried out on the concentrated extract alone [20].

2.6. Mild Steel Surface Characterization

Surface characterization of mild steel was carried out using Field Emission Scanning Electron Microscopy (FESEM). Field Emission Scanning Electron Microscopy (FESEM) analysis was performed on untreated steel as well as on steel specimens before and after immersion with the EDAG inhibitor for 7 days in 1 M hydrochloric acid solution. The analysis was conducted by examining the surface morphology of the mild steel at an accelerating voltage of 5 kV and a magnification of 5.000× to observe morphological changes resulting from immersion and the adsorption of active compounds on the steel surface [21].

3. Results and Discussion

3.1. *Asystasia gangetica* (L.) T. Anderson Leaf Extract (EDAG)

The *Asystasia gangetica* (L.) T. Anderson leaf extract (EDAG) was obtained as a brownish green powder, with an extraction yield of 13.70%.

Table 1. Mass and Yield data of the EDAG extract

Simplicia (g)	*Asystasia gangetica* (L,) T. Anderson Leaf Extract (g)	Yield (%)
550	75.4	13.70

Figure 1. EDAG extract powder

This yield value indicates that the extraction process proceeded efficiently and that EDAG contains a relatively high level of secondary metabolites [22], making it a potential source of active compounds for use as a corrosion inhibitor.

3.2. Phytochemical Analysis

Phytochemical tests were conducted to identify the secondary metabolites present in the EDAG extract. As shown in Table 2. EDAG was found to contain secondary metabolites [8] such as flavonoids, alkaloids, steroids, triterpenoids, and phenolics. However, saponins were not detected, as the test did not produce persistent foam.

Table 2. Result of phytochemical analysis of EDAG (+: present, -: absence)

Compound	Result
Flavonoids	(+)
Alkaloids	(+)
Steroids	(+)
Triterpenoids	(+)
Phenolic	(+)
Saponin	(-)

Flavonoid compounds in the EDAG extract contain -OH and carbonyl groups capable of donating electrons and forming π-interactions with Fe^{2+}, thereby generating stable complexes on the steel surface [23]. Alkaloid compounds, through nitrogen atoms possessing lone electron pairs, form coordination bonds with Fe^{2+} [24]. Phenolic compounds adsorb onto the surface via -OH groups and aromatic π electrons, whereas steroids and triterpenoids, with their large hydrophobic structures, form protective layers that cover active sites and hinder the diffusion of aggressive ions such as Cl^- [25]. The synergistic action of these compounds enhances adsorption stability and improves the inhibition efficiency on the mild steel surface.

3.3. The Corrosion Rate and Inhibition Efficiency

The corrosion rate of mild steel and the inhibition efficiency were determined using the weight loss method. This method was employed to investigate the effect of adding EDAG extract on the corrosion rate of steel in 1 M hydrochloric acid solution. Figure 2. shows the influence of extract concentration on the corrosion rate and inhibition efficiency of the steel. The graph indicates that the corrosion rate decreases as the extract concentration increases, whereas the inhibition efficiency rises with increasing concentrations of EDAG extract.

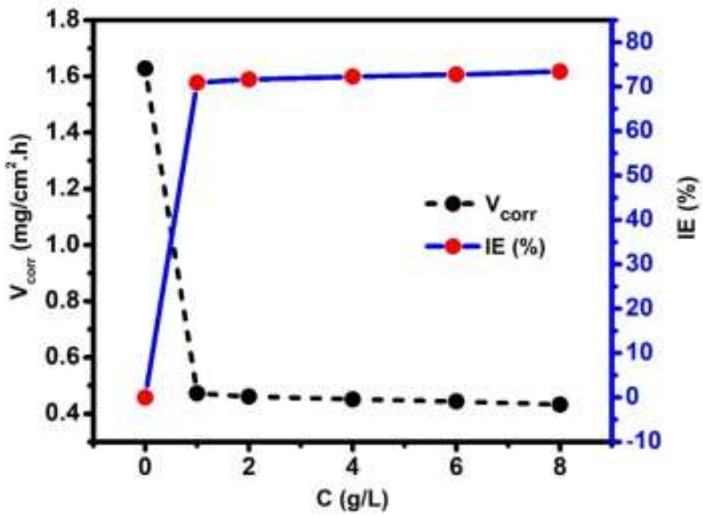


Figure 2. The effect of EDAG concentration on the corrosion rate and inhibition efficiency in I M hydrochloric acid solution

Table 3. shows that before the addition of the inhibitor, the highest corrosion rate was 1.62 mg/cm².h, however, after the addition of the inhibitor, the corrosion rate decreased to 0.43 mg/cm².h at a concentration of 8 g/L. This reduction in corrosion rate indicates that active molecules such as flavonoids, alkaloids, phenolics, steroids, and triterpenoids in the extract are adsorbed onto the steel surface, forming a protective layer that blocks contact between the mild steel and aggressive ions in the corrosive medium [26].

Table 3. The effect of variations concentration of EDAG extract on the corrosion rate, inhibition efficiency and surface coverage of mild steel in 1 M hydrochloric acid solution at 30 °C

C (g/L)	Corrosion rate (mg/cm².h)	IE (%)	Surface coverage (Θ)
0	1.62	0	0
1	0.47	70.94	0.709
2	0.46	71.65	0.716
4	0.45	72.26	0.723
6	0.44	72.73	0.727
8	0.43	73.42	0.734

These compounds contain aromatic groups rich in π electrons and heteroatoms such as O and N that possess lone electron pairs, which can be donated to the vacant orbitals of Fe^{2+}, forming coordination bonds or stable adsorption complexes on the mild steel surface [27]. As the inhibitor concentration increases, the number of adsorbed molecules also increases, thereby raising the surface coverage (Θ) and improving the inhibition efficiency [28]. The maximum inhibition efficiency obtained was 73.42% at a concentration of 8 g/L. These results demonstrate that EDAG extract effectively inhibits corrosion by adsorbing onto the mild steel surface.

In the acidic hydrochloric acid medium, functional groups in the inhibitor molecules, such as -OH and $-NH_2$, may undergo protonation. This protonation reduces their ability to donate electron pairs to the Fe surface due to electrostatic repulsion between H^+ ions and the positively charged metal surface. Consequently, the protonated inhibitor molecules exhibit lower adsorption affinity, whereas the non-protonated molecules are able to form coordination bonds with Fe^{2+}, allowing adsorption to occur. This explains how the acidic medium influences the adsorption mechanism and the efficiency of the inhibitor [29].

Adsorption isotherms were used to explain the interaction between inhibitor molecules and the steel surface [30]. Figure 3. presents the determination coefficient (R^2) values of several adsorption isotherm models evaluated to describe the interaction of EDAG extract inhibitor molecules on the mild steel surface. Based on the graph, the Langmuir model exhibits the highest R^2 value approaching 1, indicating that the adsorption process of the inhibitor follows a monolayer adsorption pattern on the steel surface [31]. Other isotherm models, such as Freundlich, Temkin, Frumkin, El Awady, and Flory Huggins show lower R^2 values. This suggests that the contribution of other adsorption mechanisms is relatively less dominant compared to the Langmuir model.

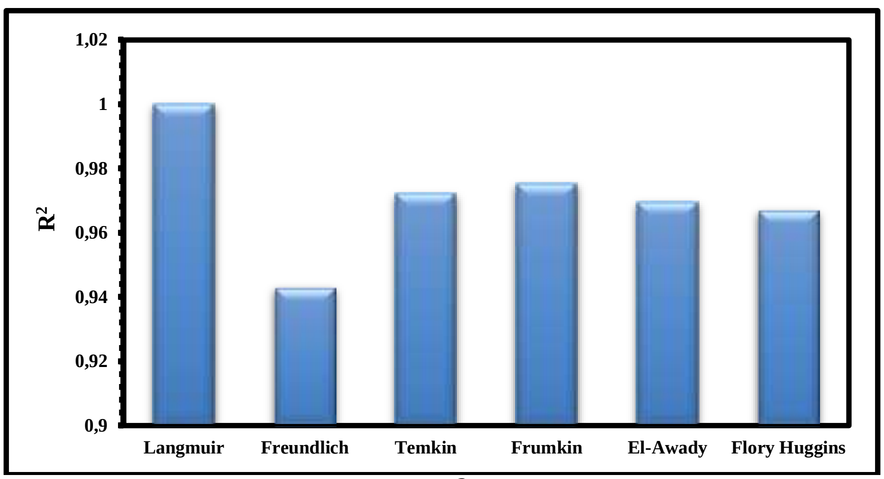


Figure 3. Determination coefficient (**R^2**) values of EDAG inhibitor from the adsorption isotherm models

The Langmuir isotherm equation can be expressed as follows:

$$\frac{C_{inh}}{\theta} = \frac{1}{K_{ads}} + C_{inh}$$

Where C is the inhibitor concentration (g/L), θ is the surface coverage (IE/100), and K_{ads} is the adsorption equilibrium constant [32]

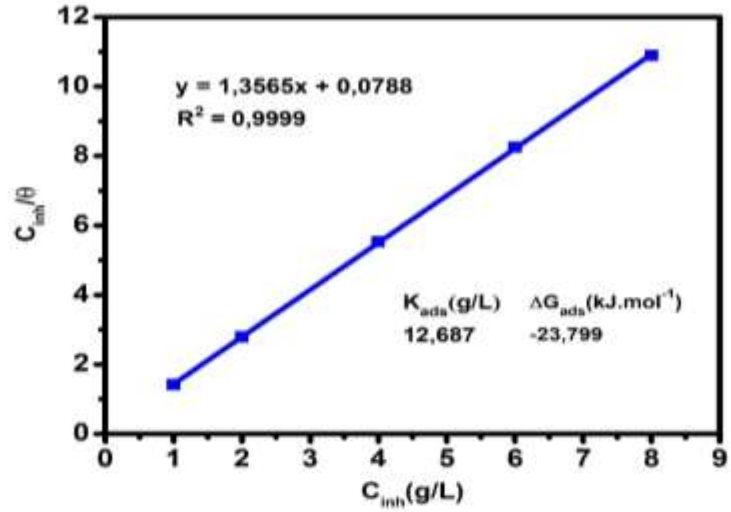


Figure 4. Langmuir adsorption isotherm plot for steel corrosion with EDAG extract

Figure 4. shows the linear Langmuir adsorption isotherm curve illustrating the relationship between C_{inh}/θ and C_{inh} at various concentrations of EDAG extract, with a determination coefficient (R^2=0,9999). The K_{ads} value is obtained from the intercept of the linear equation, where the magnitude of K_{ads} indicates the strength of the adsorption interaction between the EDAG extract molecules and the steel surface. The standard free energy of adsorption (ΔG_{ads}) can be calculated from the K_{ads} value using the following equation:

$$K_{ads} = \frac{1}{999} \exp\left(-\frac{\Delta G_{ads}}{RT}\right)$$

Where 999 represents the concentration of water in the solution and R is the molar gas constant (8.314 J mol^{-1} K^{-1}). The value of ΔG_{ads} can be calculated from the obtained K_{ads}. The adsorption constant (K_{ads}) of 12.687 g/L indicates that the inhibitor molecules from the EDAG extract possess a reasonably strong adsorption affinity toward the mild steel surface. The magnitude of K_{ads} suggests that the active compounds in the extract are capable of interacting with the metal surface to form a protective layer that suppresses the corrosion process [33]. This is supported by the ΔG_{ads} value of -23.799 kJ/mol, which falls within the range of -20 to -40 kJ/mol, indicating a mixed adsorption mechanism involving both physical interactions such as electrostatic forces and Van der Waals interactions and chemical interactions, including coordination bonding and complex formation between the inhibitor molecules and the metal surface. The negative Gibbs free energy further confirms that the adsorption process occurs spontaneously [34].

Table 4. Langmuir adsorption isotherm plot parameters for the EDAG extract system on the mild steel surface in 1 M hydrochloric acid solution

Slope	Intercept	R^2	K_{ads} (g/L)	ΔG_{ads} (kJ/mol
1.3565	0.0788	0.9999	12.687	-23.799

3.4 UV-Visible Analysis

The UV–Vis spectrum in Figure 5 shows three curves, namely hydrochloric acid solution, EDAG extract, and hydrochloric acid with EDAG. The spectrum displays two main absorption bands in the regions of approximately 280 - 300 nm and 400 - 450 nm. The band in the 280 - 300 nm region is associated with $\pi \rightarrow \pi^*$ transitions of aromatic chromophore groups such as phenolic or flavonoid compounds, whereas the band around 400 - 450 nm corresponds to $n \rightarrow \pi$ transitions originating from carbonyl (C=O) groups or more extensive electron conjugation within the extract structure.

The spectrum of hydrochloric acid shows very low absorbance with no significant peaks, indicating that hydrochloric acid does not exhibit absorption within the UV-Vis region. In contrast, the spectrum of hydrochloric acid containing EDAG shows a shift of the absorption peak toward a higher wavelength (bathochromic shift) along with an increase in absorbance intensity, indicating the presence of interactions or complexation between the active compounds in the extract and Fe^{2+} ions. This bathochromic shift suggests the formation of metal–ligand complexes involving phenolic/flavonoid groups and other active constituents in the extract, resulting in changes to the electronic structure and the formation of new coordination bonds [35].

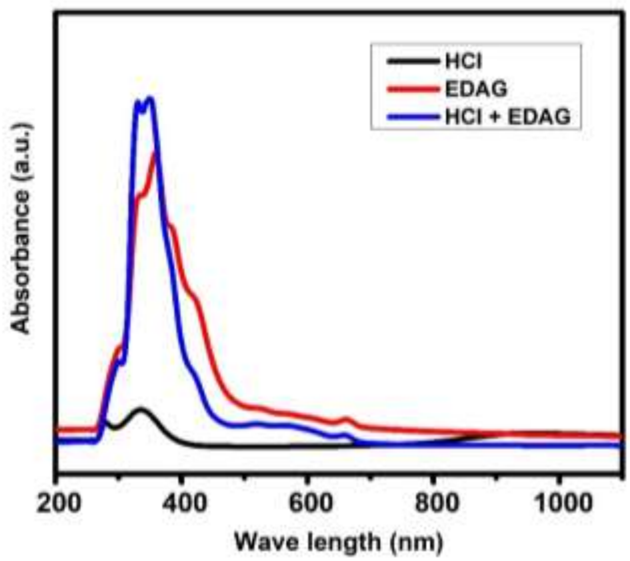
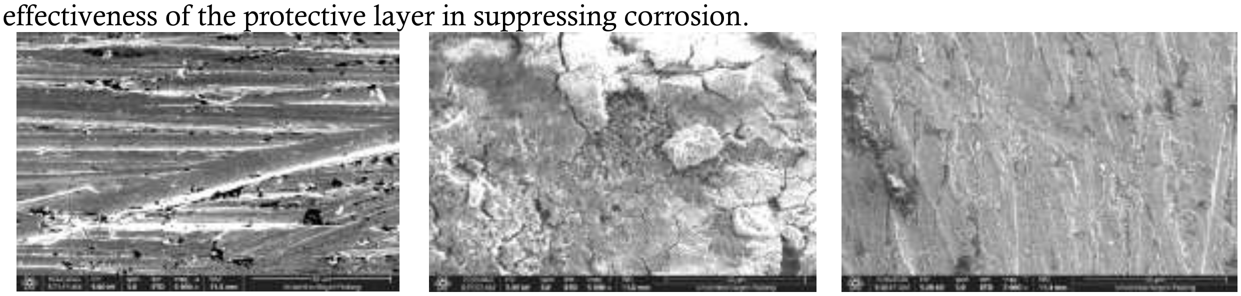


Figure 5. UV-Vis spectra of 1 M hydrochloric acid solution, EDAG extract and 1 M hydrochloric acid with EDAG

3.5 Field Emission Scanning Electron Microscopy (FESEM)

Field Emission Scanning Electron Microscopy (FESEM) was employed to examine the surface morphology of mild steel and to characterize the protective film formed by the addition of the inhibitor. This analysis aims to identify microstructural changes on the steel surface and to assess the effectiveness of the protective layer in suppressing corrosion.



(a) (b) (c)

Figure 6. FESEM of the mild steel surface at 30 µm (a) untreated steel, (b) steel immersed in 1 M hydrochloric acid and (c) steel immersed in 1 M hydrochloric acid with EDAG

Figure 6 (a). Shows the morphology of the untreated steel surface, where fine parallel lines resulting from the grinding process are clearly observed. In contrast, Figure 6 (b). Illustrates the morphology of the steel surface after corrosion, characterized by the presence of cracks and an irregular texture due to exposure to 1 M hydrochloric acid. The formation of cracks indicates that steel without inhibitor addition undergoes severe corrosive attack. Meanwhile, Figure 6 (c). Demonstrates a noticeably smoother surface, with several cracks partially covered following the introduction of 8 g/L EDAG. This improvement confirms that the adsorbed inhibitor molecules form an effective protective layer that reduces direct interaction between the steel substrate and the corrosive medium, thereby lowering the corrosion rate [19].

4. Conclusion

Based on the conducted research, it can be concluded that the addition of *Asystasia gangetica* (L.) T. Anderson leaf extract (EDAG) at higher concentrations into the 1 M hydrochloric acid corrosion medium effectively reduces the corrosion rate. The lowest corrosion rate was obtained at a concentration of 8 g/L with a value of 0.43 $mg/cm^2 \cdot h$ and a maximum inhibition efficiency of 73.42%. The adsorption behavior follows the Langmuir isotherm model and corresponds to a mixed-type adsorption mechanism. UV–Vis analysis revealed a wavelength shift indicating interactions and the formation of complex compounds between the EDAG inhibitor and the steel surface, leading to the development of a protective layer. Surface morphology analysis using FESEM further confirmed that EDAG was stably adsorbed onto the steel surface. Therefore, the organic inhibitor derived from *Asystasia gangetica* (L.) T. Anderson leaf extract exhibits strong potential to be developed as a green corrosion inhibitor for steel protection in acid-based industrial processes such as pickling, acid cleaning, and oil and gas operations

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